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IN-DUCT VISCOUS FLOW PRESSURE DISTRIBUTION ON A BODY WITH BOUNDARY LAYER CONTROL

G. C. Lauchle

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It is well known that the static pressure distribution of an axisymmetric body operating within the boundaries of a duct such as a wind or water tunnel test section is altered from that observed in a free stream because of solid blockage and horizontal buoyancy effects. Because potential flow solutions can account only for the solid blockage, auxiliary analysis must be performed to account for the viscous (horizontal buoyancy) effects. One such analysis has been performed by this author ~~[J. Hydronautics, Vol. 13, April 1979, pp. 61-67]~~, where it was assumed that boundary layer development occurred in a natural, flat plate-like

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20. manner over the test body and duct walls. In this report, a modification of that analysis is presented which permits one to analyze bodies with boundary layer control. In addition to the theoretical formulation, a numerical example is presented to illustrate the effect on the pressure distribution of a 0.318 m diameter body with surface suction operating in a 1.22 m diameter duct.

Subject: In-Duct Viscous Flow Pressure Distribution on a Body With Boundary Layer Control

References: See page 11.

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Acknowledgments: This work has been performed at the Applied Research Laboratory of The Pennsylvania State University under a contract with the Naval Underwater Systems Center IPUV Block Program, Newport, RI. The continued support by the Naval Sea Systems Command, Code NSEA-63R31 for tasks related to laminar flow technology is also gratefully acknowledged and Mr. J. Crust is to be credited for his effort in the computer programming.

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A	the blocked area between the body and duct wall
A_o	area of duct
Cp	pressure coefficient
ΔCp	pressure coefficient correction
ΔCp_i	components of ΔCp ($i = 1, 2, \ldots$)
C_{f_b}	body skin friction coefficient
C_Q	suction coefficient
D_{max}	maximum diameter of the body
I	the momentum integral, Eq.'s (9) and (10)
L	total body length
ℓ	length from forward stagnation point of body to beginning of duct
ℓ_o	distance from nose of body to point on duct wall where turbulent boundary layer begins
r	radius coordinate
U_∞	free-stream velocity in duct far upstream of body
u	local fluid velocity
u_o	reference velocity in potential flow computation
x	axial coordinate where origin is ℓ_o upstream from nose of the body
$\bar{x}$	body axial coordiante ($x - \ell_o$)
x'	dummy variable of integration
δ	boundary-layer thickness
ν	kinematic viscosity
ρ	fluid mass density
τ	wall shear stress
θ	independent variable in Equations (15a) and (15b)

Special Subscripts

b	refers to body
I	refers to inviscid
V	refers to viscous
w	refers to duct wall

INTRODUCTION

The pressure distribution on a body of revolution will be altered from that observed under free stream conditions when the body is operated in a closed conduit such as the test section of a wind or water tunnel. The differences are a result of blockage effects due to the walls of the test section and to viscous effects originating on both the walls and the body under investigation. As pointed out by this author [1,2]*, the solid blockage effects can be accurately predicted with currently used potential flow computer codes [3 through 7], while the viscous effects must be accounted for through subsequent analysis of the potential flow results. Such analysis was presented in References [1] and [2] under the assumption that the boundary layer flow evolved in a natural flat plate-like manner over the body and duct walls.

In some instances, the body under investigation may have a form of boundary layer control such as heating, cooling, suction, or blowing. Under these conditions, the boundary layer growth and the distribution of wall shear stress will be significantly different from those calculated or measured without boundary layer control. An extension of the original analysis [1,2] is therefore required in order to allow for the modified boundary layer development over bodies that use boundary layer control. This report gives the details of this extension. It is assumed that the boundary layer velocity profile and wall shear stress distributions are available as input for this analysis. Hoffman [8] has developed general computational codes, based on the work of Cebeci and Smith [9], to predict these parameters for bodies with roughness, cooling, heating, suction, or blowing. As a numerical example, the analysis presented herein will be used to predict the in-duct body pressure distribution of a typical axisymmetric body with and without surface suction.

ANALYSIS

Given the body shape and cylindrical duct diameter ($2r_w$), it is relatively straightforward to calculate the inviscid, in-duct body pressure distribution [3 through 7]. This potential flow pressure distribution is denoted by $Cp_I(\bar{x})$, where $\bar{x}$ is the body axial coordinate, Figure (1a). As discussed in the previous papers [1,2], Cp_I should be corrected to the reference velocity, U_∞ which would occur at the beginning of an assumed infinitely long duct. For finite distances (ℓ) from the nose of the body upstream, the flow velocity is u_o which is slightly higher than U_∞. For most potential flow calculations of this type, $2\ell + L$ represents the duct length, where L is the body length and then

$$Cp_I = 1 - (1 - Cp)\left(\frac{u_o}{U_\infty}\right)^2 \quad . \tag{1}$$

In Equation (1), $Cp(\bar{x})$ are the pressure coefficient values computed by the numerical code being used.

*Numbers in brackets refer to references at end of report.

For the case of viscous flow in the duct, boundary layers will develop on the body and on the duct walls. The origin of duct boundary layer flow is assumed known and is at $\bar{x} = -\ell_o$ as schematically expressed in Figure (1b). Note also that a new coordinate (x) originates at $\bar{x} = -\ell_o$ and that the velocity at x = 0 is U_∞. A goal of the present analysis is to derive expressions for a pressure coefficient correction (ΔCp) such that Cp_I may be conveniently corrected for the viscous flow effects, i.e.,

$$Cp_V = Cp_I + \Delta Cp \quad . \tag{2}$$

This derivation was carried out in References [1] and [2] for assumed flat-plate like boundary layer development, where now, the analysis will be modified to account for the non-conventional types of boundary layer development that occur on bodies with some form of boundary layer control. The boundary layer velocity profile on the body is assumed known and is denoted by u_b. Likewise the wall shear stress on the body is τ_b.

Beginning with Equation (16) of Reference [1] or Equation (24) of Reference [2]

$$\Delta Cp = \sum_{i=1}^{4} \Delta Cp_i \quad , \tag{3}$$

where ΔCp_4 was shown to be negligible and

$$\Delta Cp_1 = 2 \left(\frac{A_o}{A}\right)^2 - \frac{4\pi}{AU_\infty^2} \int_{r_b}^{r_w} u^2 r \, dr \quad , \tag{4}$$

$$\Delta Cp_2 = - \frac{4\pi}{A\rho U_\infty^2} \int_{\ell_o}^{x} r_b \, \tau_b \, dx' \quad , \tag{5}$$

$$\Delta Cp_3 = - \frac{4\pi r_w}{A\rho U_\infty^2} \int_{0}^{x} \tau_w \, dx' \quad , \tag{6a}$$

$$\simeq - 0.144 \, \pi \left(\frac{r_w}{A}\right) \left(\frac{\nu}{U_\infty}\right)^{1/5} x^{4/5} \quad . \tag{6b}$$

The approximation of Equation (6b) results from the assumption that a flat plate-like turbulent boundary layer develops on the duct wall with an origin at x = 0. This part of the total correction [Equation (3)] needs no further discussion here because it will be unaffected by body boundary layer control.

In the computational schemes of Hoffman [8] and most others, the wall shear stress is expressed in non-dimensional skin friction coefficient form:

$$C_{f_b} = \frac{\tau_b}{1/2\ \rho\ U_\infty^2} \quad . \tag{7}$$

Hence, given C_{f_b}, Equation (5) may be computed directly by numerical integration, i.e.,

$$\Delta Cp_2 = -\frac{2\pi}{A}\int_{\ell_o}^{x} r_b\ C_{f_b}\ dx' \quad . \tag{8}$$

The pressure coefficient correction ΔC_{p_1} is evaluated for a body with boundary layer control by first writing

$$I \equiv \int_{r_b}^{r_w} u^2 r dr = \int_{r_b}^{r_b+\delta_b} u_b{}^2 r dr + u_V{}^2 \int_{r_b+\delta_b}^{r_w-\delta_w} r dr + \int_{r_w-\delta_w}^{r_w} u_w{}^2 r dr \quad . \tag{9}$$

The assumption of flat plate turbulent boundary layer development on the duct wall, reduces Equation (9) to:

$$I = \frac{1}{2}\, u_V{}^2\, [(r_w - \delta_w)^2 - (r_b - \delta_b)^2] + \frac{7}{9}\, u_V{}^2 r_w \delta_w$$

$$- \frac{7}{16}\, (u_V \delta_w)^2 + u_V{}^2 \int_{r_b}^{r_b+\delta_b} \left(\frac{u_b}{u_V}\right)^2 r dr \quad , \tag{10}$$

where u_b/u_V would be the non-dimensional velocity profile for the body with (or without) boundary layer control. It is assumed here that $u_V = u_e$ (edge velocity) and is negligibly affected by the tunnel wall meaning that the velocity profiles may be calculated using Cp_I. Also, δ_b is the distance from the body surface to where $u = 0.99\ u_V$. Elimination of $u_V{}^2$ from Equation (10) requires the continuity equation:

$$A_o U_\infty = 2\pi \int_{r_b}^{r_w} u r dr \quad . \tag{11}$$

Writing

$$A_oU_\infty/2\pi = \int_{r_b}^{r_b+\delta_b} u_b rdr + u_V \int_{r_b+\delta_b}^{r_w-\delta_w} rdr + \int_{r_w-\delta_w}^{r_w} u_w rdr \quad , \tag{12}$$

one can easily verify that

$$A_oU_\infty/2\pi = \frac{1}{2} u_V \left[(r_w - \delta_w)^2 - (r_b + \delta_b)^2\right]$$

$$+ u_V \left[\frac{7}{8} r_w\delta_w - \frac{7}{15} \delta_w^{\ 2}\right] + u_V \int_{r_b}^{r_b+\delta_b} \left(\frac{u_b}{u_V}\right) rdr \quad . \tag{13}$$

Solving Equation (13) for u_V, squaring and substituting into Equations (10) and (4) one finds that

$$\Delta Cp_1 = 2\left(\frac{A_o}{A}\right)^2 - \frac{2A_o^{\ 2}\left[(r_w-\delta_w)^2 - (r_b+\delta_b)^2 + \frac{14}{9} r_w\delta_w - \frac{7}{8}\delta_w^{\ 2} + 2\int_{r_b}^{r_b+\delta_b} (u_b/u_V)^2 \, rdr\right]}{\pi A\left[(r_w-\delta_w)^2 - (r_b+\delta_b)^2 + \frac{7}{4} r_w\delta_w - \frac{14}{15}\delta_w^{\ 2} + 2\int_{r_b}^{r_b+\delta_b} (u_b/u_V) \, rdr\right]^2} \ . \tag{14}$$

Equations (8) and (14) are seen to require numerical integration of the skin friction coefficient and boundary layer velocity profile, respectively.

EXAMPLE

To illustrate the effect of one type of body boundary layer control on the pressure distribution of an axisymmetric body which operates in the closed cylindrical working section of a water tunnel, some numerical calculations based on the preceding analysis will be presented. The body selected for this example is one designed for laminar flow control through distributed surface suction. The body is 2.900 m long and has a cylindircal mid section 0.318 m in diameter. The calculations to follow assume it will operate in a water tunnel test section which is 1.22 m in diameter. The nose of the body was designed by Smith [10] and is described by equations of the Lemniscate type [11]. In particular, the nose contour, as defined back to the tangent point where the cylindrical mid body begins is given by:

$$\bar{x} = 3.6\, D_{max} \left(1 - 1.241 \sqrt{\sin 2\theta}\, \cos\theta\right)/2 \tag{15a}$$

$$r_b = D_{max} \left(1 - 2.149 \sqrt{\sin 2\theta}\, \sin\theta\right)/2 \tag{15b}$$

where $0 \leq \theta \leq 30°$. The tangent point defines the nose length and is at $x = 0.572$ m. The tailcone originates at $x = 2.134$ m and is described by a 6th order polynomial. Because the subject calculations are not accurate over the afterbody [1,2] region there is no need to give the mathematical details of the afterbody here.

Researchers at the Naval Ocean Systems Center in San Diego, CA have performed boundary layer stability analysis (unpublished) on this particular body design and have concluded that the suction distribution given in Figure 2 should result in full laminar flow over the body for an extensive speed range. Here, the suction coefficient C_Q is defined in the usual manner as u_n/u_e, where u_n is the fluid velocity normal to the body. Typical laminar boundary layer velocity profiles are given for two velocities and two different axial locations in Figures 3 through 6. These profiles were computed using Hoffman's computer code [8] which uses the potential flow in-tunnel body pressure distribution calculated from the program of Friedman [4].

The calculated potential flow and viscous flow (with suction) pressure distributions for this body are given for three velocities in Figures 7 through 9. The pressure coefficient corrections summarized by Equation (3) can be seen on these figures as the difference between the dash-dot line and the dashed line. As expected, the correction is most important at low speeds. The effect of surface suction on these viscous flow pressure distributions is demonstrated in Figures 10 through 12. The "without suction" results are based on laminar boundary layer velocity profiles computed with $C_Q = 0$. It must be emphasized, however, that at these velocities and lengths, the boundary layer will almost certainly be turbulent over most of the body length with no surface suction. Since turbulent boundary layers are thicker than laminar ones, the differences between the pressure distributions of Figures 10 through 12 are considered the minimum to be expected.

CONCLUSIONS

It has been the purpose of this note to extend an analysis [1,2] for the effects of viscous flow on in-duct body pressure distributions to account for the non-conventional boundary layer development over bodies with some form of boundary layer control such as heat, suction, blowing, or cooling. The resulting formulation is similar to that for natural flat plate-like body boundary layer development but is more complicated because the boundary layer velocity profiles for the body with boundary layer control need to be specified at all axial stations of interest and then numerically integrated. Aside from this numerical inconvenience, the computations are straightforward. An example was given for a typical body of revolution with surface suction. Based on the computed pressure distributions for this body operating in a 1.22 m diameter duct, the differences between the pressure coefficients with and without suction were seen to be significant; typically, on the order of 10 percent at $C_p \cong -0.2$. Although examples were not presented for other types of boundary layer control, similar differences would be expected.

The usefulness of the current analysis appears to be in the area of laminar flow control experiments, where a given system might be evaluated in a wind or water tunnel. Because of the complexity of such bodies it would prove difficult to instrument them with static pressure orifices to obtain precise pressure distribution data. (Precise data are required because transition locations are very sensitive and known to move with only slight changes in pressure gradient.) Since these data are required in order to execute properly most transition prediction methods, a method such as this one would seem to be required in order to account for some of the many variables that enter into such an experiment. Unfortunately, there are no currently available experimental pressure distributions for bodies with boundary layer control, so verification of the current analytical extension of the theory of References [1 and 2] cannot be performed at this time. However, it is emphasized that the work documented in References [1 and 2] does include experimental results for a body without boundary layer control that do indeed verify the theoretical approach taken and assumptions made.

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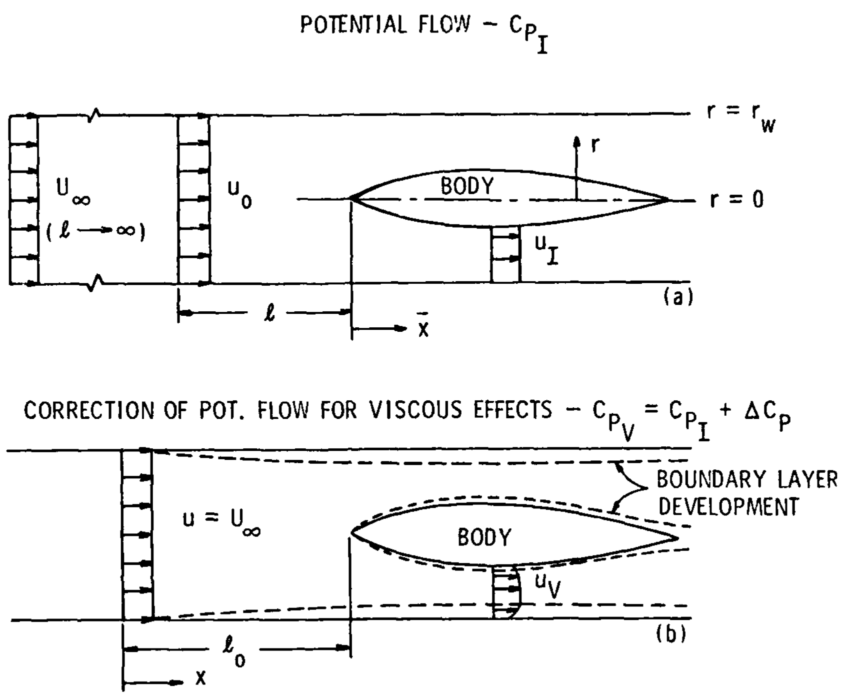

Figure 1. a) Potential Flow Over a Body in an Infinitely Long Cylindrical Duct; b) A Schematic Description of Boundary Layer Development on the Body and Duct Wall, Noting That $u_V \neq u_I$

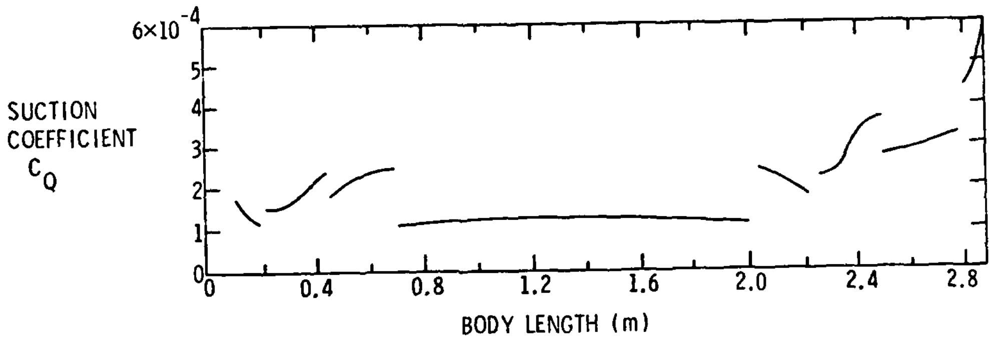

Figure 2. Theoretically Established Suction Distribution for Laminar Flow Control of Body Considered in the Numerical Example

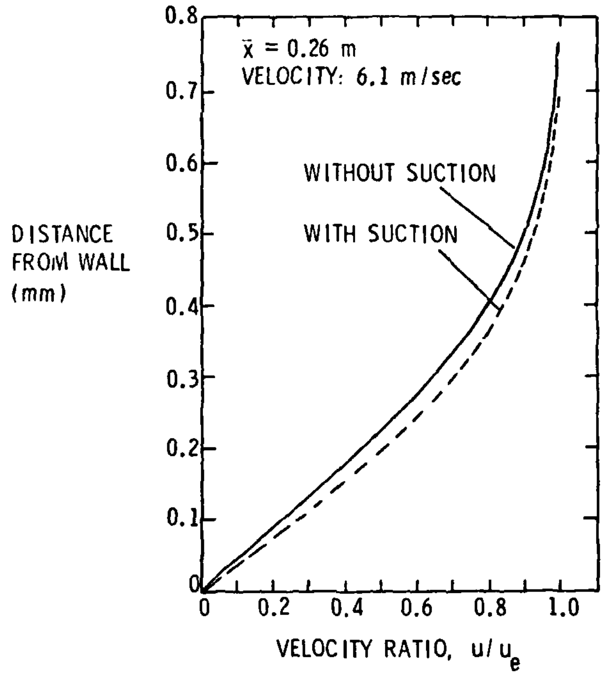

Figure 3. Body Boundary Layer Velocity Profiles Computed With and Without Suction at $\bar{x}$ = 0.26 m and 6.1 m/sec

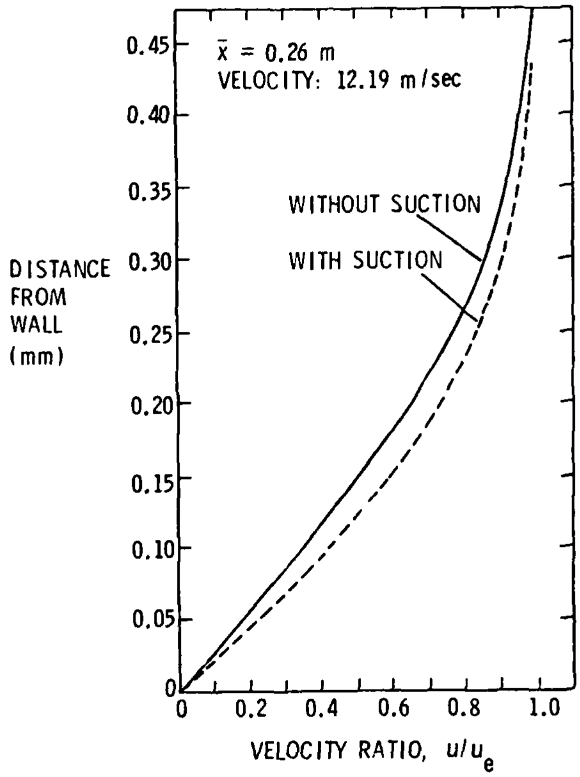

Figure 4. Body Boundary Layer Velocity Profiles Computed With and Without Suction at $\bar{x}$ = 0.26 m and 12.19 m/sec

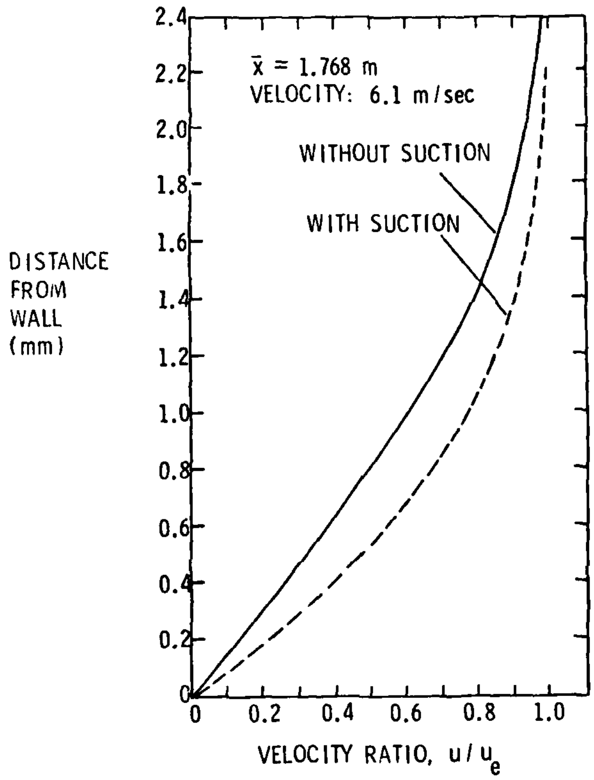

Figure 5. Body Boundary Layer Velocity Profiles Computed With and Without Suction at $\bar{x}$ = 1.768 and 6.1 m/sec

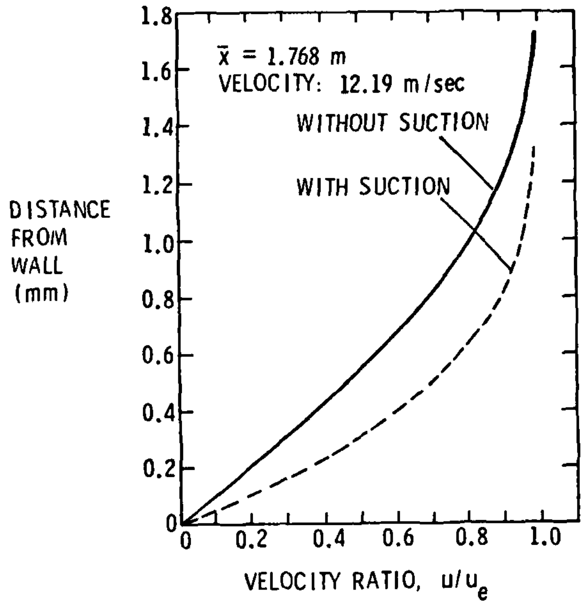

Figure 6. Body Boundary Layer Velocity Profiles Computed With and Without Suction at $\bar{x}$ = 1.768 m and 12.19 m/sec

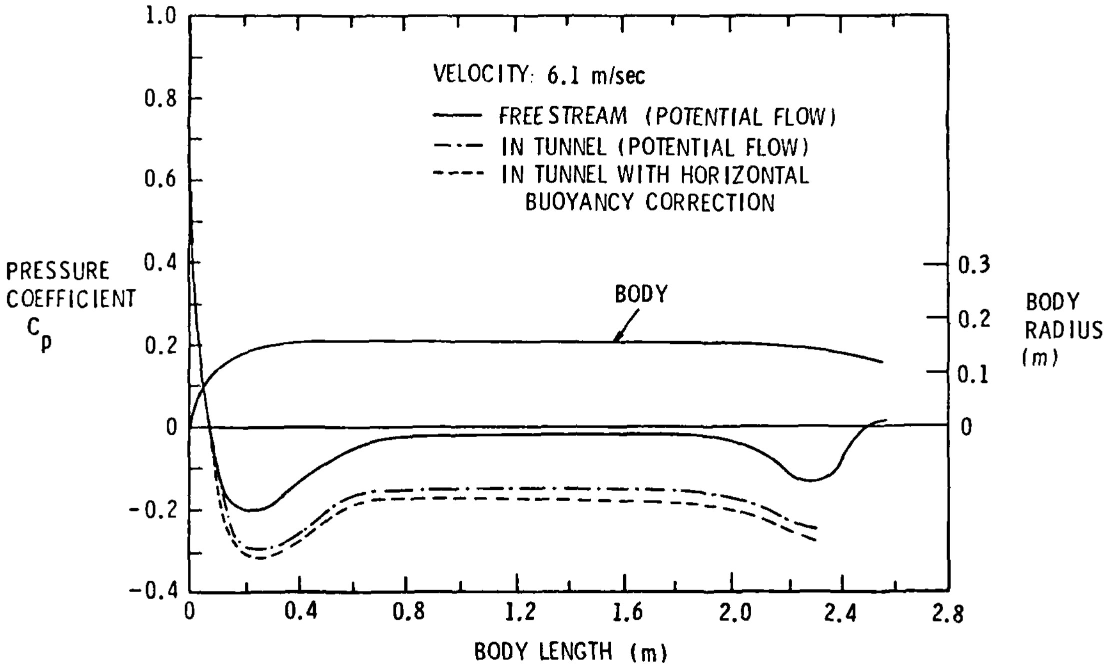

Figure 7. Computed Potential Flow Pressure Distributions of Body Operating in Free Stream and in a 1.22 m Diameter Duct. Also, the In-Duct Result Corrected for Viscous Effects When Suction is Applied and for U_∞ = 6.1 m/sec

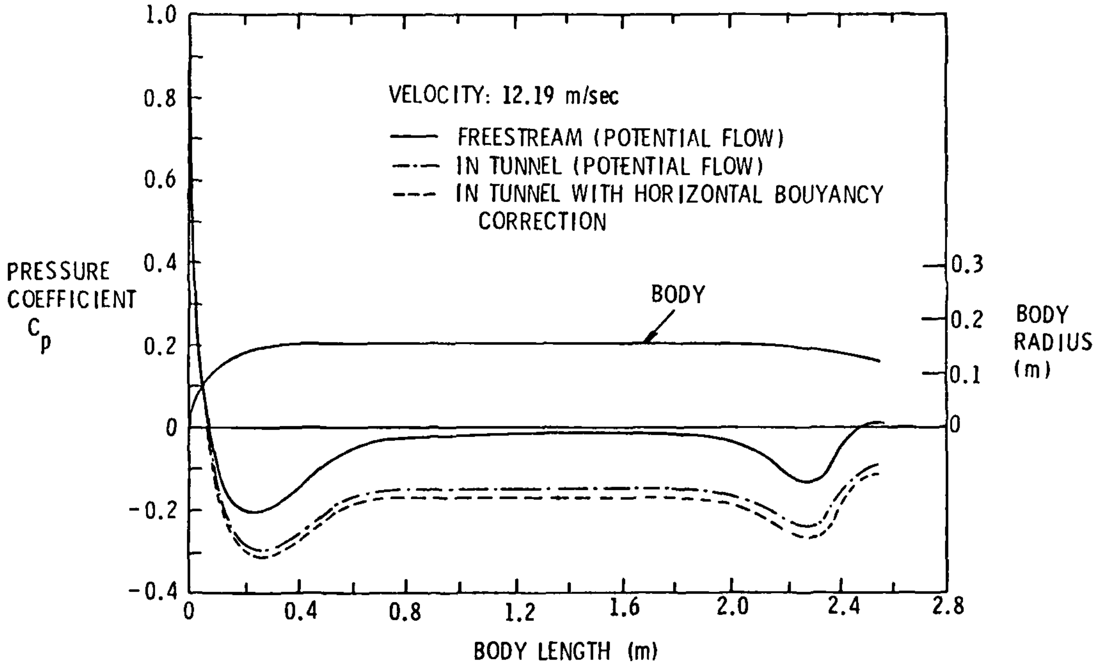

Figure 8. Computed Potential Flow Pressure Distributions of Body Operating in Free Stream and in a 1.22 m Diameter Duct. Also, the In-Duct Result Corrected for Viscous Effects When Suction is Applied and for U_∞ = 12.19 m/sec

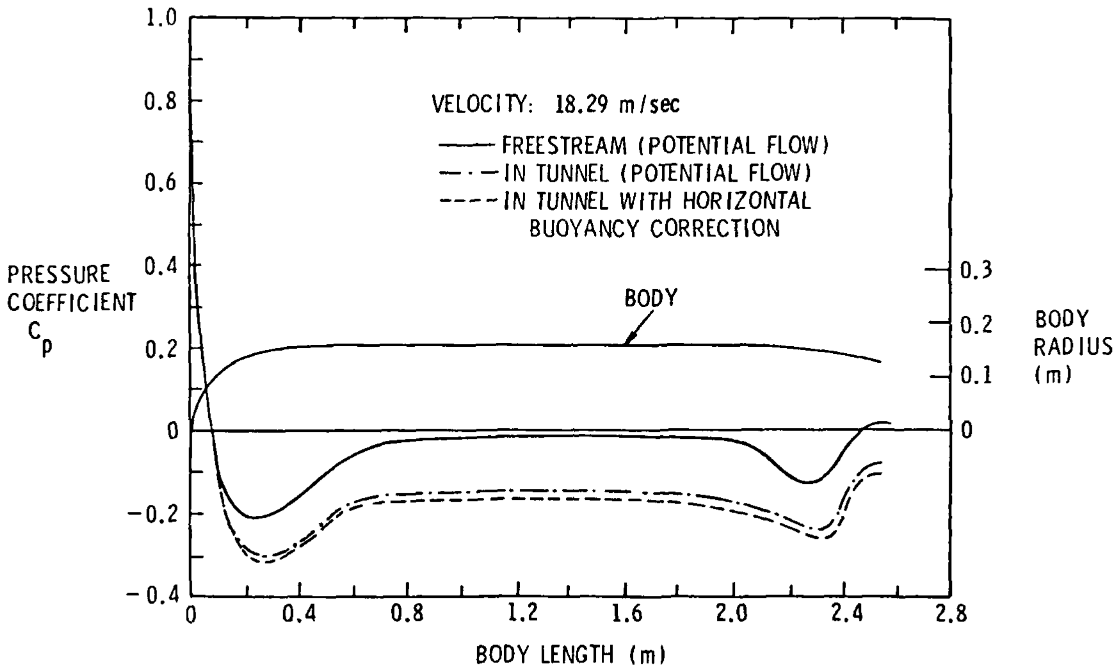

Figure 9. Computed Potential Flow Pressure Distributions of Body Operating in Free Stream and in a 1.22 m Diameter Duct. Also, the In-Duct Result Corrected for Viscous Effects When Suction is Applied and for U_∞ = 18.29 m/sec

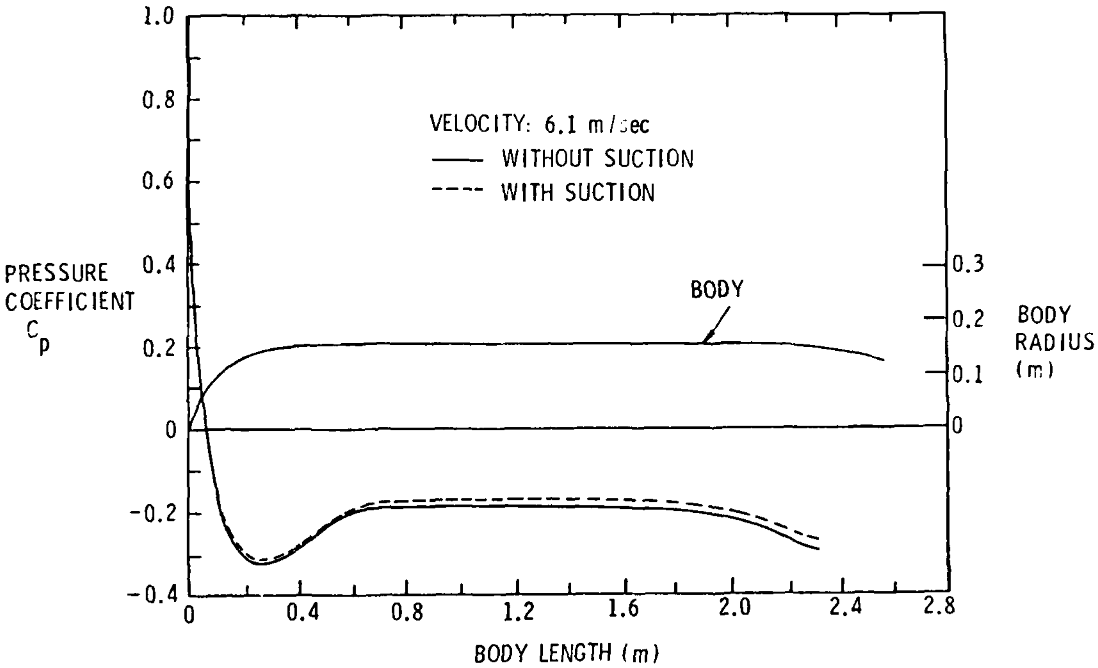

Figure 10. Comparison of the In-Tunnel Viscous Flow Pressure Distributions With and Without Body Suction at 6.1 m/sec

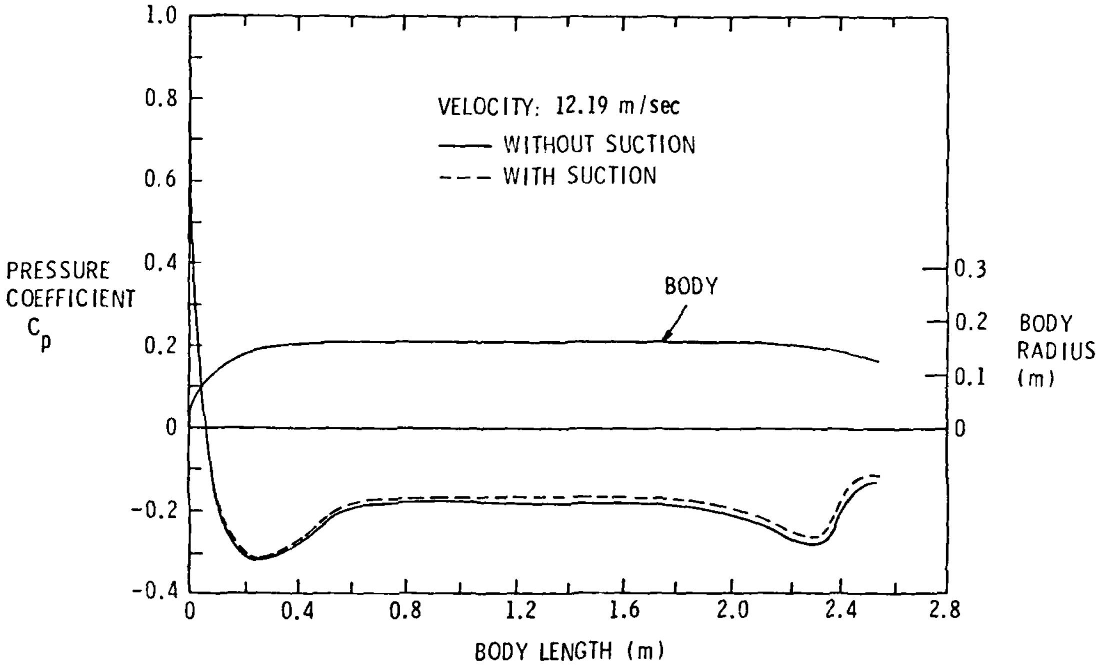

Figure 11. Comparison of the In-Tunnel Viscous Flow Pressure Distributions With and Without Body Suction at 12.19 m/sec

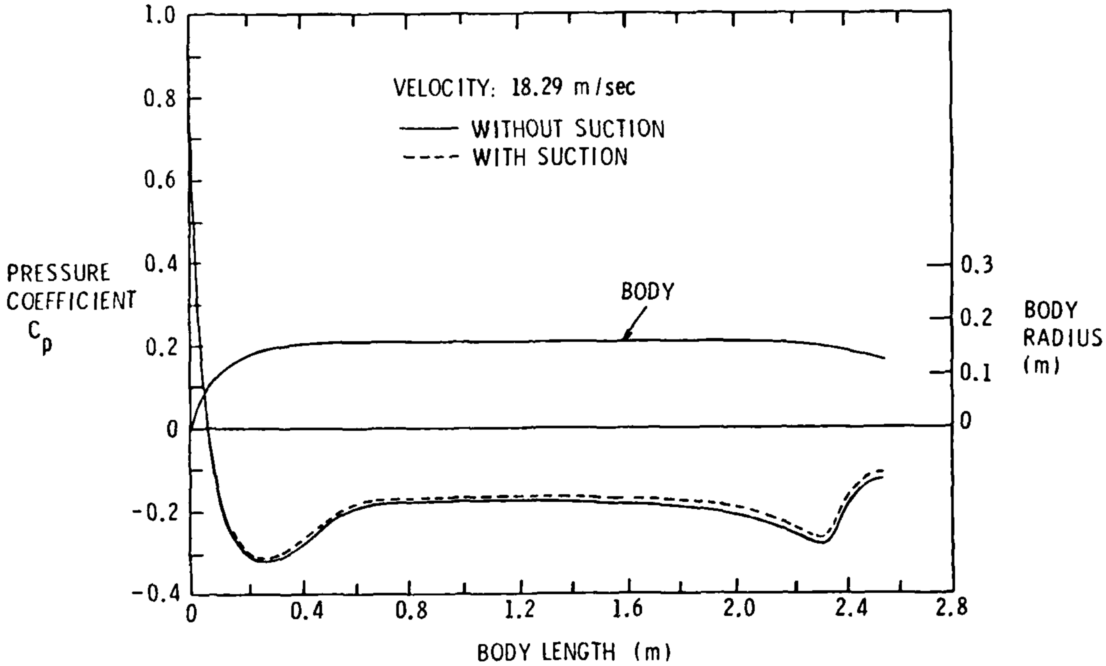

Figure 12. Comparison of the In-Tunnel Viscous Flow Pressure Distributions With and Without Body Suction at 18.29 m/sec

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